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Failure of leachate collection systems is expected to be a problem in the operation of hazardous waste disposal facilities, just as failure of drainage systems has been a problem at agricultural sites. The principal failure mechanisms include sedimentation, clogging by biological, chemical and biochemical materials, and mechanisms which do not involve clogging including pipe deterioration, pipe displacement and exceeding design capacity. Operating experience with leachate collection systems indicates that all of the failure mechanisms have occured in the field, although experience with chemical and biochemical precipitation is limited. In a survey of 22 waste disposal facilities which had leachate collection system problems, 14 experienced problems attributable to errors in design, construction or operation. The remaining 8 experienced problems that could likely have been avoided through system maintenance. Designing to avoid failure includes careful pipe location, fallback systems or redundancy, allowing for maintenance requirements and addressing specific failure mechanisms. Construction must involve adequate quality assurance and may require special construction techniques. Operation of leachate collection systems to avoid failure includes regular inspection and system maintenance to find and address problems before they become too serious.

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AVOIDING FAILURE OF LEACHATE COLLECTION SYSTEMS AT HAZARDOUS WASTE LANDFILLS

Jeffrey M. Bass[1]

Failure of leachate collection systems is expected to be a problem in the operation of hazardous waste disposal facilities, just as failure of drainage systems has been a problem at agricultural sites. The principal failure mechanisms include sedimentation, precipitation of biological, chemical and biochemical materials, and mechanisms which do not involve clogging including pipe deterioration due to chemical attack or corrosion, differential settling and exceeding design capacity. Operating experience with leachate collection systems indicates that all of the principal failure mechanisms have occurred in the field, although experience with chemical and biochemical precipitation is limited. In a survey of twenty waste disposal facilities which had leachate collection system problems, twelve experienced problems attributable to errors in design, construction or operation. The remaining eight experienced problems that could likely have been avoided through system maintenance. Designing to avoid failure includes careful pipe location, redundancy, allowing for maintenance requirements and addressing specific failure mechanisms. Construction must involve adequate quality assurance and may require special construction techniques. Operation to avoid failure includes regular inspection and system maintenance to find and address problems before they become too serious.

Introduction

Failure, caused by a variety of mechanisms, is common to drainage systems of all kinds. Leachate collection systems, the drainage systems which remove excess liquid accumulation above liners at land disposal facilities, are no exception. Failure of leachate collection systems, however, may be a greater cause for concern than failure, for example, of agricultural drainage systems. This is especially true for leachate collection systems at hazardous waste disposal facilities. Undetected failures may cause leachate to build up on top of the liner. This can lead to failure of the liner system and contamination of groundwater. Furthermore, failures which are detected may be difficult to repair, and replace-

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ment is no longer a simple last resort since excavation of hazardous wastes would be required.

In order to minimize the potential for system failure, it is first necessary to understand the mechanisms by which failure can occur. Then, guidelines on design, construction, inspection and maintenance can be given to help prevent these mechanisms from occurring, or at least to minimize their impact if they should occur. A schematic of a typical leachate collection system is given in Figure 1.

Failure Mechanisms

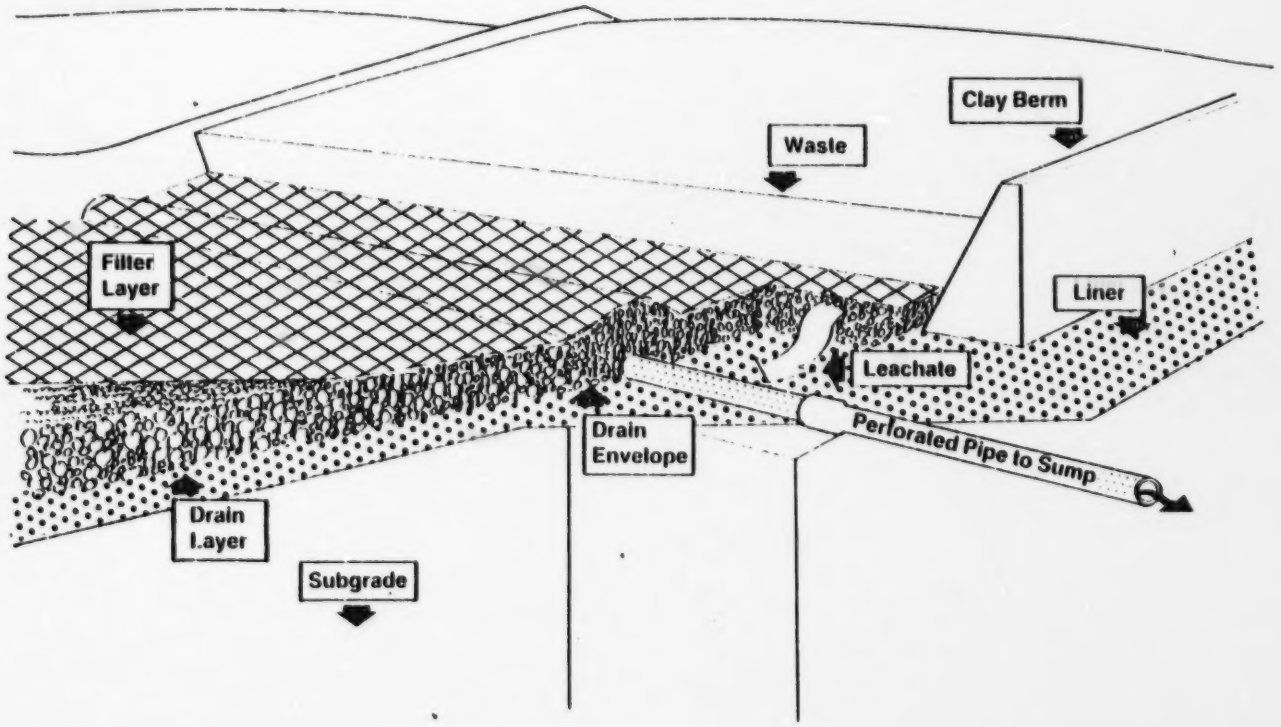
Theoretical Basis

Failure of drainage systems can be caused by a variety of mechanisms. Some of the most common of these are mechanisms which lead to system clogging. Clogging is defined as the physical buildup of material in the pipe or drain layer such that flow is significantly restricted. Other failure mechanisms which do not involve clogging, per se, include differential settling, deterioration of the drainage pipe due to chemical attack or corrosion, and exceeding design capacity (for example due to undersizing of drainage pipes). Here, failure occurs because liquid is not adequately removed from the system, even though there may not be physical blockage of system components.

Clogging can be caused by the buildup of soil, biological organisms, chemical precipitates, and combinations of the three. This buildup can occur either in the pipe or in the surrounding drainage or filter layers. Soil clogging (sedimentation or siltation) requires both a source of soils and a mechanism by which they can settle out. Surrounding soils can enter the drainage or filter layers if the grain size distribution in these layers is too large. Cedergren (1967), for example, indicates that the surrounding soils will remain in place if the pore spaces in the filter layer are small enough to hold the 85 percent size of the soil. Alternatively, soil from the drainage and filter layers will enter the pipe if the grain size distribution is too small, or the pipe slot size is too large. Once soils have entered the pipe they can settle out if the flow is insufficient to keep them entrained. Low flow rates can occur throughout the pipe if the slope is too shallow, or locally in areas of hydraulic perturbations such as poorly designed or installed pipe joints, turns, or intersections. Sedimentation of soils in the pipe is one of the most widely recognized clogging mechanisms.

Biological clogging occurs when organism growth fills the pipe or interstices of the drain envelope and interferes with normal system flow. The growth of biological material in a drainage system is dependent on the presence of micro-organisms together with the appropriate nutrients, growth conditions and energy sources. In particular, Vitreoscilla, a filamentous slime forming organism, and

FIGURE 1
SCHEMATIC OF A TYPICAL LEACHATE COLLECTION SYSTEM



Pseudomonas, a common soil bacteria, are known clogging agents when iron is not present. Enterobacter is also known to contribute to clogging of the area abutting drain envelopes (Young, et al., 1982). Factors thought to contribute to biological clogging include carbon to nitrogen ratio in the leachate, rate of nutrient supply, concentration of polyuronides, temperature, and soil moisture (Avnimelech and Nevo, 1964; Kristiansen, 1981).

Clogging by chemical precipitation can occur as the result of simple chemical processes or more complex biochemical processes. Chemical processes include the precipitation of calcium carbonate, magnesium carbonate (rhodochrosite) and other insoluble forms (such as sulfides and silicates). Chemical precipitates form under basic, neutral or slightly acidic conditions (pH greater than about 4), and are also dependent on the hardness and total alkalinity of the leachate. Precipitation can occur due to changes in pH, changes in pressure or partial pressure of CO_2, or evaporation of residual liquid (Bass, et al., 1983).

The principal biochemical precipitates are $Fe(OH)_3$ and FeS, although manganese compounds may also be involved. The biochemical process for iron depends primarily on the availability of dissolved (free) ions (influenced by redox potential, pH, and complexing agents) and on the presence of iron-reducing bacteria. The precipitate is generally mixed with a biological slime made up of the oxidizing bacterial colonies, creating a product which is quite adherent and which can very rapidly block flow through a drainage system. The precipitates produced as a result of biochemical activity are generally quite different in form or structure from those resulting from chemical processes alone, and may be more effective in leading to clogging. Chemically precipitated iron, for example, does not as readily adhere to plastic pipe and is more porous than biochemically precipitated iron (Ford, 1979).

There are at least three types of failure possible which do not involve clogging of the drainage system. The first can occur if the system or a component of the system is undersized such that the amount of liquid to be removed is greater than the amount which can be handled by the system. Underestimation of maximum design flow can be the result of a design error, an unanticipated event which causes flows in excess of design limits (such as cover failure in a landfill), or a condition which was inadequately accounted for in the original design (such as groundwater flow). The second type of failure is differential settling which can cause insufficient or inconsistent slope and displacement or crushing of drainage pipes causing a buildup of leachate in localized areas. Problems with slope or pipe displacement and crushing can also be a result of errors in design or construction. Finally, pipe deterioration can be caused by chemical attack (acids, solvents, oxidizing agents) or corrosion.

Expected Performance at Hazardous Waste Facilities

Most of the information on the failure mechanisms described above is found in the literature on agricultural drainage systems, where experience with failed drains is common. Experience with leachate collection systems, on the other hand, is limited. It is possible, however, to analyze the susceptibility to failure of leachate collection systems at sanitary and hazardous waste landfills relative to the performance of agricultural drainage systems based on an understanding of these failure mechanisms, and on the operational characteristics expected in each type of system. The results of such an analysis, conducted by Bass et al., 1984, are given in Table 1.

Table 1 indicates that pipe crushing and deterioration are more likely to occur at hazardous waste leachate collection systems than at agricultural drainage systems. All other failure mechanisms are less likely to occur. This conclusion is based in part on the assumptions that more careful design, lower pH (generally), and wider variety of chemicals are expected in hazardous waste facilities than in agricultural drainage systems. All of the failure mechanisms, however, are possible at hazardous waste disposal facilities; there is no conceptual basis for ruling out any of the mechanisms for hazardous waste leachate collection systems. Failure of leachate collection systems is therefore expected to occur at some (undetermined) percentage of land disposal facilities. The likelihood of failure occurring at any given facility will depend on site-specific considerations, including system design, construction quality, waste characteristics and operating procedures.

Experience at Hazardous Waste Facilities

The theoretical analysis of failure mechanisms and the potential for clogging of leachate collection systems, discussed above, was checked with data from actual experience. Tables 2 through 4 summarize the results of a telephone survey conducted in late 1983. The survey included thirteen individuals from companies or agencies which design, construct, operate and/or regulate landfills which have leachate collection systems. The purpose of the survey was to determine whether the theoretical mechanisms discussed above have indeed occurred in the field. The purpose was not to provide a statistical basis to determine service life or to quantify the potential for failure of leachate collection systems. Information was obtained based on the experience of the individuals interviewed. Information based on general experience is noted in the comments of Table 2. Also, the facility type is given as "not specified" when the information is based on general information and/or the facility name was not provided.

Several observations can be made from Tables 2 through 4. First of all, failure was reported at only one hazardous waste site. The significance of this observation is unclear. There are likely

TABLE 1
RELATIVE POTENTIAL FOR CLOGGING OF LEACHATE COLLECTION SYSTEMS

Mechanism	Agricultural Drains	Sanitary Landfills	Hazardous Waste Landfills	Significant Differences
Sedimentation	*	-	-	More careful design and construction expected
Chemical ($CaCO_3$)	*	*	-	Lower pH
Biochemical (Ochre, Fe)	*	*	-	Toxicity to indigenous bacteria, lower pH
Biological	*	*	-	Toxicity to indigenous bacteria, lower pH
Differential Settling, crushing	*	+	+	Compaction, greater equipment loading
Deterioration	*	*	+	Chemicals, solvents, lower pH expected
Exceed Design Capacity	*	-	-	Daily cover restricts leachate flow to system

- = less likely; + = more likely; * = some likelihood.

Source: Bass, et al., 1984.

TABLE 2

SUMMARY OF EXPERIENCE WITH LEACHATE COLLECTION SYSTEM PROBLEMS

Failure Mechanism	Facility Type	Cause	Comments
Sedimentation	NS	C	no filter installed
Sedimentation	NS	U	general experience
Sedimentation	co-disposal	U	in 1 year old system
Sedimentation	co-disposal	U	of gravel layer and pipe
Sedimentation	municipal	U	general experience
Sedimentation	NS	C	general experience
Pipe breakage	NS	O	by clean-out equipment if bends greater than 22°, general experience
Pipe breakage	municipal	D	differential settling, improper bedding
Pipe separation	municipal	C	joints not glued
Pipe deterioration	NS	D	problems with ABS pipe, general experience
Pipe deterioration	hazardous	O	from acid or solvent disposed of in wrong cell
Tank failure	co-disposal	D	leachate holding tank
Capacity exceeded	co-disposal	D	under design, other problems noted
Outlet inadequate	co-disposal	D	caused leachate buildup
Biological growth	industrial	D	100 ft. long biological growth flushed out under high pressure
Biological growth	municipal	U	reduction in flow every 2 years; flushed out
Biological growth	municipal	U	of filter fabric
Biological growth	co-disposal	U	on 3/4 inch stone, not clogged
Chemical precipitation	municipal	O	EPA test cell, not clogged
Chemical precipitation	co-disposal	U	iron oxide, not clogged

C = construction related; O = operation related; NS = not specified;

U = undetermined; D = design related.

TABLE 3
SUMMARY BY MECHANISM

Mechanism	Facility Type: Municipal	Co-disposal/ industrial	Hazardous	Not Specified	Total
Sedimentation	1	2	-	3	6
Pipe breakage/ separation	1	-	-	2	3
Pipe deterioration	-	-	1	1	2
Other non-clogging problems	-	3	-	-	3
Biological growth	2	2	-	-	4
Chemical precipitation	1	1	-	-	2
Biochemical precipitation	-	-	-	-	0
TOTAL	5	8	1	6	20

TABLE 4
SUMMARY BY CAUSE

Design related	6
Construction related	3
Operation related	3
Unknown	8

fewer hazardous waste than municipal and co-disposal facilities to draw from. Moreover, companies may be less likely to volunteer information on problems in hazardous waste leachate collection systems. It cannot be concluded based on this observation alone that failure is less likely to occur in hazardous waste leachate collection systems. It is interesting to note, however, that pipe deterioration, the mechanism which occurred at the hazardous waste landfill, was predicted in Table 1 as being more likely to occur in hazardous waste facilities.

A second observation which can be made has to do with the distribution of experience in Table 3. Sedimentation and the non-clogging mechanisms are the most common. Experience with biological growth, although more limited, is significant. Three cases of biological clogging were reported. In one case, a 100 foot long biological mass, which looked like an immense black worm, was jetted out of a pipe at a paper mill sludge disposal facility. Little experience was found with chemical and biochemical precipitation; only two cases of chemical buildup without clogging were reported. In a survey conducted by Young, et al. (1982), however, clogging with biochemical ochre was reported in a sanitary/industrial facility in Delaware. This facility used 100 collection wells in and around the waste fill for its leachate collection system.

Finally, in Table 4, twelve of the twenty problems can be related to errors or difficulties in facility design, construction or operation. In addition, most of the problems where the cause could not be pinpointed could likely have been avoided through improved system design, construction, or inspection and maintenance (operation). Specific examples from these tables will be discussed in the following section.

Prevention

Since both theoretical analysis and actual experience indicate that failure mechanisms common to agricultural drainage systems are expected to be active in leachate collection systems, it is necessary to determine how failure via these mechanisms can be avoided. The survey results show that, in most cases, the problems experienced could have been prevented through better design, construction and operation practices. This section therefore discusses methods in each of these three areas which are considered to be important in avoiding system failure.

Design

Design considerations to prevent failure include:

- pipe location
- redundancy
- maintenance features
- addressing specific mechanisms

Pipe location and placement is critical to the performance of leachate collection systems. Crushing or displacement due to equipment loading and/or differential settling is a well-recognized problem; one case is noted in Table 2. A pipe is best protected when it is placed in a trench with careful consideration given to loading conditions and proper bedding. The trench provides added protection for the pipe, especially during placement of the first lift of waste when the pipe is most susceptible to crushing. Pipe strength determination procedures and bedding requirements can be found in U.S EPA, 1983 draft.

Redundancy in design is important to minimize the effect of failure mechanisms when they occur. The system should be able to remove liquid from any point in the facility by more than one pathway. One of the primary ways to provide redundancy is to design collection laterals such that drainage requirements can be met by the gravel layer alone if flow through the pipe is restricted. In addition, laterals should be spaced so that if one lateral is totally blocked, liquid can be removed through an adjacent lateral.

One of the most important design considerations to prevent failure is designing the system to facilitate inspection and maintenance. Access should be provided to all parts of the system. This includes the placement of manholes and cleanouts so that maintenance equipment, discussed below, can reach any length of pipe. The design should consider minimum pipe size, distance between access points, and maximum angles negotiable by such equipment. For example, some jet cleaning equipment requires at least a four inch pipe and can operate in straight runs up to 1000 feet in length. In one example in Table 2, cleanout equipment is reported to break pipes at bends greater than 22 degrees.

Finally, leachate collection systems can be designed to avoid specific clogging mechanisms. For example, sedimentation can be avoided through proper selection of grain size distribution in the filter material to exclude solids (U.S. EPA, 1983 draft), and by providing minimum slope and avoiding hydraulic perturbations to maintain flow velocity during leachate collection so that solids can not settle out. Maintaining flow velocity will also help prevent buildup of biological and chemical materials. Cell specific selection of construction materials can help avoid chemical compatibility problems at hazardous waste facilities. Anaerobic conditions can be maintained to avoid chemical precipitation (for example, using U-traps at pipe outlets), although anaerobic biological activity will increase.

Construction

A leachate collection system must be constructed according to design specifications to be effective. Specific construction problems which can cause leachate collection system failure include (Bass, et al., 1984 draft):

- the use of materials with specifications other than the ones in the approved design;

- foreign objects (e.g., rocks, clumps of soil, construction tools) left in drainage system piping which plug or restrict leachate flow and may not be removable using designed maintenance procedures;

- neglecting to install materials in the location specified in the design;

- neglecting to follow procedures specified in the design;

- siltation of filter or drainage layers resulting from improper upgradient drainage during construction and/or careless construction techniques;

- the use of improper construction equipment and the improper placement of materials which cause damage to system components, such as crushing or misalignment of pipes due to vertical loading of heavy equipment or soil dumping; and

- non-conforming layout of the leachate collection system, such as the misalignment of piping joints or improper slopes and elevations of piping causing inefficient drainage.

Construction quality assurance (CQA) is needed to verify that the completed leachate collection system meets or exceeds the design requirements. This involves monitoring and documenting the quality of materials used and the conditions and manner of their placement. CQA serves to detect variations from design, whether as a result of error or negligence of the contractor, and to provide for suitable corrective actions before wastes are accepted at the facility. Without proper CQA, problems with leachate collection systems due to construction, like the two specific examples noted in Table 2, would not be discovered until the system failed during operation (Bass, et al., 1984 draft).

Methods used in CQA testing are listed in Table 5. Additional information on CQA for leachate collection systems, including a detailed description of the methods in Table 5, can be found in Bass, et al., 1984 draft.

In addition to CQA, specific construction methods may be important in avoiding failure mechanisms. John Pacey of Emcon Associates (Personal interview, 11/83), for example, suggests that surface water control during construction is important to avoid sedimentation in drainage lines. He recommends placing pipe in trenches in small sections and completing each section before starting on the next. This minimizes the amount of surface sediments which are washed into the drain during construction. Construction techniques which are important to system performance should be specified in the design and monitored by the CQA program.

TABLE 5

CQA TEST AND MONITORING PROCEDURES

Component	Test	Commonly Used Test Method(s)
Soils	Observation	----
	Surveying	Standard Methods
	Particle-size distribution	ASTM D 422; AASHTO T 27
	In-place density	ASTM D 2922; AASHTO T 191, T 205
	In-place soil permeability	ASTM D 3385; AASHTO T 215
Geotextiles	Observation	----
	Record Specimens	----
Pipe	Observation	----
	Pipe Installation	Standard Methods
	Low air pressure test for leakage on non-pressure solid pipe	----
	Pressure, solid pipe	Section 13, AWWA C600
	Inspection of completed pipe network	Standard sewer cleaning methods

(Continued)

TABLE 5

CQA TESTS AND MONITORING PROCEDURES
(Continued)

Component	Test	Commonly Used Test Method(s)
Concrete Structures (Manholes and Collection Tanks)	Observation	----
	Sampling fresh concrete	ASTM C 172
	Consistency	ASTM C 143
	Making and curing concrete test specimens	ASTM C 31; AASHTO T 141
	Unit weight, yield and air content	ASTM C 138; AASHTO T 121
	Visual inspection of formwork, placement and curing process	----
Mechanical Equipment	Observation	----
	Startup and performance testing	As per manufacturer's instructions
Monitoring Equipment and Controls	Observation	----
	Startup and performance testing	As per manufacturer's instructions
Electrical	Observation	----
	Circuit testing	In accordance with standards & procedures of NEC, IEEE, UL, NEMA, NFPA, etc.

Source: Bass, et al., 1984 draft.

Operation

Operational procedures can cause failure of leachate collection systems even if the system is well designed and constructed. An example of this is given in Table 2 where acid or solvent caused deterioration of a pipe which was not designed to receive such wastes.

Alternatively, operational procedures, particularly inspection and maintenance, can prevent failure from occurring by locating and correcting the problem before it becomes too serious. Without proper inspection and maintenance, problems may not be noticed until the sump runs dry, at which point simple maintenance techniques may no longer be effective. Regular flushing of the system which produced the 100 foot "worm" would likely have prevented the buildup from occurring. At the second biological growth site, for example, flushing every two years prevents the growth from getting too serious. In addition, some types of clogs, such as biochemical precipitation of iron, are relatively easy to remove when young, but are difficult, if not impossible, to flush out once they have matured (Ford, 1980). For these types of deposits, early detection is needed to avoid possible excavation and replacement of the clogged drain.

Inspection methods are intended to determine whether failure mechanisms are active in the leachate collection system. Periodic inspection techniques include indirect methods such as monitoring flow at outlets or access points, monitoring leachate level within the facility, correlating leachate quantity with rainfall data, and correlating leachate quality with clogging indicators, such as the presence of iron reducing bacteria. Direct inspection methods which can be performed periodically include TV or photographic inspection of drainage pipes and checking the physical continuity of the pipes with sewer cleaning equipment. Direct methods are limited to use in drain pipes, since the drainage and filter layers are not accessible to physical inspection.

In addition to regular or periodic inspections, special inspections should be performed at significant times in the life of the facility. These include:

- as-built inspection, as part of the CQA plan, to verify continuity of the pipe network after construction.
- re-verification of continuity after the first lift of waste is placed.
- other tests to locate and diagnose suspected problems.

Maintenance techniques are used as routine measures to prevent failure mechanisms from getting underway or far enough along to affect system flow. The two examples of flushing in Table 2 are not maintenance measures; the clogging was so advanced that flushing is

considered a remedial or repair action. Flushing of the second system every year to avoid the significant reduction in flow would be considered a maintenance measure.

Experience with maintenance techniques at leachate collection systems is lacking. It seems that the system is generally only "maintained" when repair is required. Although maintenance and repair often involve the same methodologies, regular maintenance may be the more cost-effective option since a less intensive effort may be required, and since some problems which can be avoided by maintenance cannot be easily corrected once they begin to restrict flow.

The simplest maintenance technique is flushing of the pipe network. This can be done using water or leachate by gravity flow or using low pressure jet cleaning equipment. Flushing and jetting serve to remove sedimentation and immature precipitation before substantial buildup can occur. Cleaning with low pressure jets (50 psi) after placement of the first lift of waste and periodically thereafter is recommended in U.S. EPA, 1983 draft.

A second technique is mechanical cleaning. This utilizes standard sewer cleaning techniques such as roto-rooters, snakes, pigs, buckets, sewer balls, etc. Mechanical techniques perform basically the same function as flushing, by dislodging sediments and immature deposits before they can cause problems. Mechanical cleaning is also a good check on the continuity of the drains, and can discover crushed or displaced pipes, as well as areas of more serious clogging.

Control of some failure mechanisms can also be accomplished by controlling waste inputs. Minimizing nutrients, adding biocides, and maintaining a low pH may be effective in reducing biological activity in the leachate collection system, although the effectiveness of this technique has not been tested. Alternatively, maintaining a neutral pH and avoiding the disposal of solvents and oxidizing agents may be useful in preventing the deterioration of system components. Waste which the system is not designed to handle should also be avoided.

There are currently no techniques available for the maintenance of the drainage envelopes or filter layers. The effectiveness of flushing is limited to the pipe. Certain chemical techniques developed for other drainage systems (SO_2 gas, hydrogen peroxide, acid treatment) may be applicable to drainage layers in leachate collection systems, although considerable testing would be required. Compatibility of the chemicals with the waste disposed of at the facility must also be considered.

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